REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE (*DD-MM-YYYY*)	2. REPORT TYPE	3. DATES COVERED (*From - To*)
28-02-2011	Final	01-06-2007 to 30-11-2010

4. TITLE AND SUBTITLE
Utilizing Spectrum Efficiently (USE)

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-07-1-0456

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Purdue University, West Lafayette, IN
University of Michigan, Ann Arbor, MI
University of Florida, Gainesville, FL

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-OSR-VA-TR-2012-0194

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
In this final report, some results of work that was supported by the Air Force Office of Scientific Research under Grant FA9550-07-1-0456 are described. The report begins with a general description of the collaborative research performed for the Complex Communications Networks Program. Next, new results of work performed during the period of Grant FA9550-07-1-0456 are presented. This work is further explained and developed in our recent publications and in the theses of graduate students, who were supported by the grant. During the period of activity corresponding to this report, research was performed at Purdue University, the University of Michigan, the University of Florida, and Ohio State University.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (*Include area code*)
U	U	U	UU		

UTILIZING SPECTRUM EFFICIENTLY (USE)

A Final Report

Submitted to the Air Force Office of Scientific Research

resulting from

Grant No. FA9550-07-1-0456

by

J. Lehnert, J. Shea, N. Shroff, W. Stark, and T. Wong

As part of the research supported by the

Complex Communications Networks Program

of the

Air Force Office of Scientific Research (AFOSR)

February 2011

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ABSTRACT

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1. INTRODUCTION

In June of 2007, a collaboration was begun with Purdue University, the University of Michigan, and the University of Florida to perform research on the efficient use of spectrum. The effort included Ohio State University later in the program when one of the researchers moved his work to that location. This final report directs the reader to the references listed at the end for details of work developed under the program. A sampling of student theses are also provided at the end of the list of references.

In the following, we choose a few areas of collaborative work and results to highlight.

2. SUMMARY OF RESEARCH FOCUSED AT THE UNIVERSITY OF FLORIDA

2.1 Introduction

Research efforts at the University of Florida on using spectrum efficiently included several thrusts based on exploiting channel agility, node cooperation, and information protection across multiple layers in a wireless network.

2.2 Exploiting Channel Agility

Aspects of channel agility involving both the physical layer and the MAC layer were examined during the research program and integrated with the efforts at the other universities.

2.2.1 Physical Layer

In order to realize channel agility in the physical layer, the research involved robust channel estimation and tracking techniques for fast varying wireless channels. Modeling a fast-varying wireless channel by a linear state-space, the investigated tracking algorithm incorporated *a priori* (possibly inaccurate) information about the channel state to combat uncertainties in the state-space model, initial states, and noises. The details of the development are given in [15,16]. The research demonstrated [16] that the proposed algorithm can achieve excellent channel tracking performance in the presence of an unknown noise, requiring only a few silent symbols prior to signal transmission (such silent periods are usually incorporated into practical transmission protocols) for the algorithm to roughly estimate the noise characteristics (i.e., to obtain rough *a priori* information about the noise).

2.2.2 MAC Layer

In the MAC layer, the research involved the use of the physical broadcast nature of the wireless channel to simultaneously send independent information to multiple users over the same frequency band. Our research has shown in [40] that the use of practical methods like two- or three-level superposition coding in multiband operation can achieve close-to-optimal spectral efficiency in a fading downlink environment. Extensions of the superposition coding design to support multicasting with the help of network coding have also been proposed in [23, 35].

2.3 Node Cooperation

Various aspects of cooperation among nodes in a communication network were studied.

2.3.1 Cooperative Transmission

The research activity investigated node cooperation by first compiling an extensive review of existing physical-layer coding techniques for some standard multi-terminal network models in [1]. Use was made of some of these basic physical-layer signaling components to support cooperative transmission of information from a source to a destination in a wireless network. Employing these basic components, simple information flow designs were constructed to achieve the optimal diversity-multiplexing tradeoff for a simple relay channel [8]. Extensions were made to our flow-based cooperative design to wireless networks with more complicated topologies, including a fully connected wireless cluster [7, 32], a parallel relay network [11, 31], a cooperative multiple-access channel [6, 29], and a cognitive relay network [17].

2.3.2 Resource Allocation

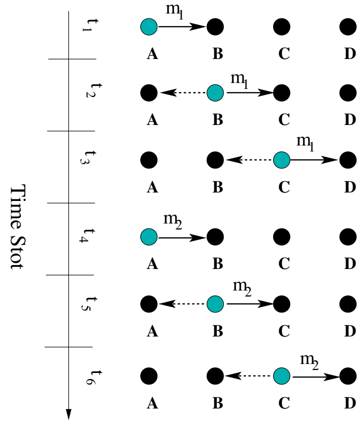
To make node cooperation agile, investigations were made of resource allocation problems in the flow-based designs described above as well as other cooperative networks. These resource allocation problems were cast as games played by different nodes in the network. For a standard fading multiple-access channel, solutions were obtained for the resource allocation problem in the presence of channel information

uncertainties by playing a bargaining game between the two users in [24]. For a distributed cooperative network [2, 30], the resource allocation problem was solved by playing a pricing game among the users.

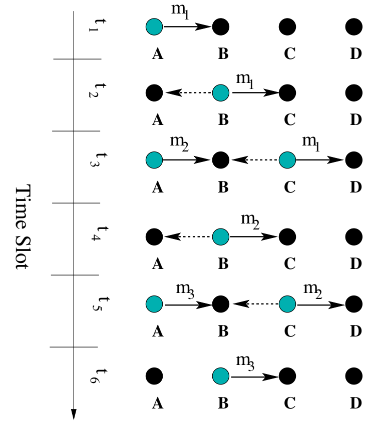
2.3.3 Overlapped Transmissions

The designs based on physical-layer coding techniques mentioned above are not the only approach to implement node cooperation. A network-layer based node cooperative technique that we refer to as *overlapped transmission* [10, 38]was also developed. To briefly explain overlapped transmission, a four-node linear network with a uni-directional transmission session as shown in Fig. 2.1(a) was considered. The assumption was made that the nodes can communicate only with the adjacent nodes, and operate in the half-duplex mode. Node A transmits packets to node D through multihop routing. One possible transmission sequence using conventional scheduling is shown in Fig. 2.1(a), in which it takes three time slots for a packet from A to reach D. Note that when the packet m_1 is being forwarded by the node C in time slot t_3, node A cannot transmit the message m_2 since C's transmission will cause interference at B (the interference is marked by dashed arrows). Under conventional MAC protocols employing carrier-sense multiple access with collision avoidance (CSMA/CA) like IEEE 802.11, B is blocked from receiving a packet from A in the time slot t_3.

The throughput of this network can be improved by employing overlapped transmissions as described below. An observation was made that in the time slot t_3, C forwards the packet m_1 which it received from B in the earlier time slot t_2. If B were to retain a copy of the message m_1 locally, it knows the message being transmitted by C in time slot t_3 (assuming that link-level encryption is not used and any differences in the headers are ignored). If A is allowed to transmit the message m_2 in the time slot t_3, B can use the stored information regarding m_1 to mitigate the interference caused by C's transmission. A scheduling scheme employing the idea of overlapped transmission for the four node linear network is depicted in Fig. 2.1(b). Since the transmission of the packet from A to B did not involve the allocation of a separate time slot for its transmission, a packet on an average requires only two time slots



(a) Conventional scheduling



(b) Overlapped transmissions

Fig. 2.1. Four node linear network example.

to be transmitted from A to D. In this sense, B cooperates with A and C to help their simultaneous transmission in time slot t_3. The research activity developed overlapped transmission protocols that provide throughput gains of 20%–100% or more by enhancing spatial reuse in networks using CSMA/CA [10] and the research activity also investigated the effect of overlapped transmission on TCP traffics in an ad hoc wireless network [37].

2.3.4 Geographic Transmission

Another approach to node cooperation based on geographic transmission was also developed. In geographic transmission, a packet is transmitted in the direction of the destination, but the next-hop forwarding node is selected among those nodes that are in the direction of the destination and that correctly recover the message. This is an opportunistic reception approach that takes advantage of multi-user diversity to significantly improve the probability of the packet being correctly received by a forwarding agent. However, this approach places additional burden on the energies of the mobile nodes if the forwarding scheme requires all of the next-hop neighbors

of the transmitter (that are in the direction of the destination) attempt to receive a transmitted message. The joint design of node-activation strategies and transmission rates to maximize the expected values of forward progress [3,5,21,33] as well as transport capacity [18,27] over a Nakagami-m channel under a constraint on the expected number of nodes that attempt to receive a packet were considered. It was shown that our approach offers significantly better performance than other approaches.

2.4 Information Protection

In terms of information protection, signal protection against jamming was considered.

2.4.1 Physical Layer

In the physical layer, partially coherent demodulation in an iterative, interference-mitigating receiver that can provide more than a 100% increase in the multiple-access capability of a frequency-hopping spread spectrum system [12,22] was applied.

2.4.2 MAC Layer

In the MAC layer, the the effect of intentional collision attacks on the IEEE 802.11 protocol in [25] was studied. It was shown that a simple jamming device with limited processing capability (enough to sense channel energy and cause interference) is sufficient to bring the throughput of a network to zero at very little energy expense. The jammer achieves this by pushing the stations to use the largest contention window, which increases the idle time between packet transmissions and reduces the number of packets for the jammer to interfere.

2.4.3 Random Variations

In addition, the possibility of exploiting random variations in the wireless channel to help a pair of nodes share secret information such as secret keys in the presence of a passive eavesdropper was investigated. In particular, the key capacity of the fast fading MIMO wiretap channel [4] was considered. It was also demonstrated that secret sharing between the two nodes in the presence of an eavesdropper could be achieved by hybrid ARQ schemes in [28]. We have also introduced the technique of

bit obfuscation [26] to improve the secrecy performance of these ARQ schemes.

3. SUMMARY OF RESEARCH FOCUSED AT THE UNIVERSITY OF MICHIGAN

3.1 Introduction

Research efforts at the University of Michigan on using spectrum efficiently included several topics which are outlined in the sections that follow.

3.2 Energy-Constrained Wireless Multi-Hop Networks

In [41] our research activity examined energy-constrained wireless multi-hop networks with a single source-destination pair. A network model that incorporates both the energy radiated by the transmitter and the energy consumed by the circuits that process the received signals was proposed. The rate of communication is the number of information bits transmitted (end-to-end) per coded symbol transmitted by any node in the network that is forwarding the data. The tradeoff between the total energy consumption and the end-to-end rate of communication was analyzed. The performance (either energy or rate) depends on the transmission strategy of each node, the location of the relay nodes, and the data rate used by each node. Communication strategies include the rate of transmission on each link, the scheduling of links, and the power used for each link. Strategies that minimize the total energy consumption for a given rate were found. Two communication strategies that capture the inherent constraints of some practical networks were also considered and compared with the optimum strategies. In the case of equi-spaced relays, analytical results for the tradeoff between the energy and the end-to-end data rate were provided. The minimum energy over all possible date rates was also found. Small rates incur a significant penalty because the receiver is on for a long time period, while high rates require high transmission energy. At high rates routes with fewer hops minimize the energy

consumption while at lower rates more hops minimize the energy consumption.

3.3 Energy-Bandwidth Tradeoff

In [42] the energy-bandwidth tradeoff of various relaying strategies over the AWGN channel was examined. The total energy consumption per information bit includes the receiver circuit processing energy at the relay and destination as well as the transmitted energy. With the cooperation of the source and relay, the end-to-end bandwidth efficiency can be improved while energy consumption is increased. Both decode and forward and amplify and forward strategies were considered. Energy-bandwidth tradeoffs for the decode-and-forward and amplify-and-forward relaying strategies were compared. It was shown that for low rates, the case without cooperation outperforms the case with cooperation for both strategies. However, when the energy required for processing at the receiver is ignored, it is helpful to cooperate for the amplify-and-forward scheme, while the result depends on the desired rate for the decode-and-forward scheme. It was also shown that the amplify-and-forward scheme does not achieve the minimum energy per bit at low SNR due to its noise propagation characteristic. Bounds on the minimum total energy consumption were derived and compared with the result without cooperation.

3.4 Energy and Bandwidth Efficiency for Short Packet Transmission

In [43] the trade-off between energy and bandwidth efficiency for short packet transmission systems with wireless sensor network applications in mind was investigated. Using random coding bound analysis, it was shown that 16-ary and 32-ary orthogonal modulation schemes provide reasonable balance between energy and bandwidth efficiency. Also, various channel coding schemes were compared and a conclusion that convolutional codes are nice candidates for wireless sensor network applications was made. The codes were shown to offer excellent performance and reasonable robustness to imperfections such as estimation errors.

3.5 Linear Networks

In [44] a linear network between a source and destination pair in a wireless multi-hop network was considered. The performance metric considered was the total energy consumed in order for a bit to be successfully received by the destination. The energy included transmitted energy and receiver processing energy. It was shown that a regular (equi-spaced) network is optimal in terms of minimizing the total energy consumption for an additive white Gaussian noise (AWGN) channel. Closed form expressions for the optimal rate and number of hops to minimize the total energy consumption were provided. The result was extended to general channels which satisfy sufficient conditions to guarantee convexness of the problem. The analysis demonstrated that the optimal rate and number of hops depend on the channel capacity characteristic, the amount of circuit processing energy, the end-to-end distance, and the path-loss exponent. Specifically, expressions for the optimal energy consumption were given for binary input AWGN channels and binary input hard decision AWGN channels.

3.6 Energy-Bandwidth Trade-Offs for Relaying Strategies

In [45] energy-bandwidth trade-offs for various relaying strategies over AWGN channels were investigated. For the total energy consumption per information bit, the receiver circuit processing energy was taken into account at the relay and destination. With the cooperation of the source and relay, the end-to-end bandwidth efficiency could be improved while energy consumption was increased. Depending on whether the source cooperates with the relay transmission, energy-bandwidth tradeoffs for the decode-and-forward and amplify-and-forward relaying strategies were compared. It was shown that for low rates, the case without cooperation outperforms the case with cooperation for both strategies. However when the energy required for processing at the receiver is ignored, it is helpful to cooperate for the amplify-and-forward scheme while the result depends on the desired rate for the decode-and-forward scheme. It was also shown that the amplify-and-forward scheme does not achieve the minimum energy per bit at low SNR due to its noise propagation characteristic. Bounds on

the minimum total energy consumption were derived and compared with the result without cooperation.

3.7 Communicating Over an Exclusive-Or Multiple-Access Channel

In [46] the problem of communicating over an exclusive-or multiple-access channel (XMAC) where a receiver wants to reconstruct the exclusive-or (XOR) of the incoming messages from two user nodes was considered. By allowing an intermediate node to mix incoming data from multiple links, network coding could increase network throughput significantly. For this problem, two possible network strategies were considered. First, two users could transmit data through a multiple-access channel (MAC) so that the receiver recovered each user's message separately and then computed the XOR of the two messages. We called this strategy a MAC strategy. Next, the receiver could also reconstruct the XOR of the two concurrently transmitted messages directly from the channel output. We called this a physical layer network coding (PNC) strategy. In this study, we investigated the error exponent and the cutoff rate of the XMAC. Assuming a Gaussian XMAC, it was shown that the MAC strategy performs better (in terms of cutoff rate) than the PNC strategy in the low rate region, while the PNC strategy performs better in the high rate region.

3.8 Ultra-Wideband Communication System

In [47] the performance of an ultra-wideband (UWB) communication system in the presence of pulsed Gaussian jamming was analyzed. We derived the optimum and suboptimum receivers for such a system and evaluated the system performance. Two low complexity suboptimum receivers were designed using a Gaussian approximation (linear) and the locally optimum Bayes detection (LOBD) algorithm (nonlinear). Numerical results showed that the nonlinear receiver outperformed the linear receiver when the jamming interference was strong. However, when the background noise was weak (high SNR), due to the Gaussian nature of impulsive interference, the nonlinear receiver performance converged to that of the linear receiver.

3.9 Energy-Bandwidth Tradeoff for Multi-Hop Wireless Networks

In [48] the energy-bandwidth tradeoff of an additive white Gaussian noise channel was characterized for multi-hop wireless networks with a single source-destination pair. The model for the energy consumption considered the energy radiated by the transmitters and the energy consumed by the receiver. The channel coding considered was Reed-Solomon codes with BPSK or orthogonal modulation. A threshold model was used for the successful packet reception from the error correcting capability of the channel code and symbol error probability of the modulation scheme. Then the end-to-end throughput was defined as the number of information bits successfully delivered per coded symbol across the network. The performance depended on the location of relays, the energy transmitted and the data rates used by relays. Optimum strategies minimizing the total energy consumption-per-bit for a given throughput were found. It was shown that BPSK modulation achieved higher bandwidth efficiency, while at low rates orthogonal modulation achieved higher energy efficiency. With equi-spaced relays, a closed-form expression for the energy-bandwidth tradeoff was derived and the minimum energy consumption-per-bit over possible rates was obtained as well. At low rates routes with more hops achieved the minimum energy consumption-per-bit while at high rates less hops achieved the minimum energy consumption-per-bit.

4. SUMMARY OF RESEARCH FOCUSED AT PURDUE UNIVERSITY AND PURDUE UNIVERSITY/OHIO STATE UNIVERSITY

4.1 Introduction

Research efforts at Purdue University and at a combination of Purdue University and the Ohio State University (when Prof. Ness Shroff changed the location of his work) is described in the following. The work involved a number of topics in the area of networking research and physical layer research that involved the efficient use of spectrum.

4.2 Network Coding

The problem of using network coding to enhance the overall throughput in the network was investigated. In particular, in [52], a distributed rate control algorithm for networks with multiple unicast-sessions when network coding is allowed across different sessions was developed. This solution was shown to achieve the network capacity of pairwise network coding and provided a means of resource allocation to an important class of the notoriously difficult intersession network coding problem. Building upon this work, in [53] a cross-layer approach for joint rate control and scheduling in wireless networks with pairwise intersession network coding was developed. In [54], our results were further extended to include Random Linear Intersession Network coding with selective cancellation.

The optimal rate-control problem was formulated as a convex optimization problem by exploiting the structure of our recent flow-based characterization of pairwise network coding. The formulation used pairwise coding possibilities between any pair of sessions, where any coded symbol is formed by coding over at most two origi-

nal symbols. The objective function was the sum of the utilities based on the rates supported by each unicast session. Working on the Lagrangian of the formulated problem, a distributed algorithm was developed with little coordination among intermediate nodes. Each unicast session had the freedom to choose its own utility function. The only information exchange required by the source was the weighted sum of the queue length of each link, which can be piggy-backed to the acknowledgment messages. In addition to the optimal rate control algorithm, we proposed a decentralized pairwise random coding scheme that decouples the decision of coding from that of rate-control, which further enhanced the distributiveness of the proposed scheme. The convergence of the rate control algorithm was proven analytically and verified by extensive simulations. Simulation results also demonstrated the advantage of the proposed algorithm over the state-of-the-art in terms of both throughput and fairness.

4.3 Scheduling

Scheduling is a critical component of any resource allocation solution in multi-hop wireless networks. In [55], a simple, and practical, scheme that was shown to achieve provably high performance and has significantly lesser complexity than state-of-the art scheduling solutions was provided. While most works on scheduling have focused on throughput performance, in [56], sharp upper bounds on the expected delay were provided by combining techniques from Lyapunov theory and queueing theory.

4.4 Resource Allocation in Multi-Hop Wireless Networks

The award was used to develop new techniques based on a rigorous mathematical foundation for resource allocation in multi-hop wireless networks. Our research produced three main results described in subsections below.

4.4.1 Greedy Maximal Scheduling

In [57, 58] the performance of an important class of scheduling schemes, called Greedy Maximal Scheduling (GMS), for multi- hop wireless networks is characterized. While a lower bound on the throughput performance of GMS has been well known,

empirical observations suggest that it is quite loose, and that the performance of GMS is often close to optimal. In these works, a number of new analytic results characterizing the performance limits of GMS were provided. It was shown how these results can be applied to tree networks to prove that GMS achieves the full capacity region in tree networks under the K-hop interference model. An earlier version of this work won the best paper award at IEEE INFOCOM 2008, the flagship conference of the field.

4.4.2 Random-Access Based Scheduling Scheme

Motivated by the work in [57, 58], a random- access based scheduling scheme that utilizes local information and provides throughput that is comparable to that of GMS was developed. The important features of this scheme included constant-time complexity, distributed operations, and a provable performance guarantee. Analytical results showed that it guarantees a larger fraction of the optimal throughput performance than the state-of-the-art. Through simulations with both single-hop and multi-hop traffics, we observed that the scheme provides close-to-optimal throughput.

4.5 Windowing for Multicarrier CDMA Systems

In [63] the windows for achieving good multiple-access performance of multicarrier code-division multiple-access (MCCDMA) systems employing minimum mean-squared error receivers were studied. The mean-squared error (MSE) was used as the performance metric for the optimization. In a simplified two-user system, the rectangular window was found to be optimum while regarded as an inferior window in orthogonal frequency-division multiplexing systems because of its spectral inefficiency. Necessary conditions were given for improving the performances of spectrally efficient windows by exploiting the cyclic prefix and oversampling in the frequency domain.

4.6 LMSE-Based Acquisition Schemes for Multicarrier CDMA Systems

In [64] an acquisition scheme, based on the least mean-squared error (LMSE), for the symbol timing, carrier phases, and multipath gains for multicarrier code-division

multiple-access (MC-CDMA) systems was proposed. A new coefficient called the quasi-mean-squared accuracy coefficient (QMSAC) was introduced. This allowed the search for multiple optimal parameters to be split into simpler single-parameter estimates. The symbol timing was acquired with a comparison of the QMSACs followed by a linear interpolation scheme or a search of a minimizing variable. Carrier phases and multipath gain coefficients were then estimated via some algebraic computations based only on the estimated symbol timing and the QMSACs. The spreading sequence of the desired user was the only prior knowledge required for the approach. Simulation results demonstrated the near-far resistance of the approach and showed that the error performance of minimum mean-squared error (MMSE) detection with acquired parameters was only a few decibels worse for the considered channel than the performance obtained with perfect knowledge about the channel impulse response.

4.7 Joint Optimization of Power Allocation and Cooperation in Wireless OFDM Networks

In [67] it was shown how wireless communication networks with more than one antenna can be used to enhance the quality of transmission with transmit diversity. However, it was pointed out that wireless devices such as mobile phones may not allow more than one antenna because of limits on size and complexity. Cooperative communications were examined to create virtual antenna systems for circumventing this problem. This technique achieved a diversity gain by using a combination of the relayed signal and the direct signal. A dual optimization method for non-convex problems was used to jointly optimize the power allocation and the scheduling of wireless cooperative OFDM systems. We found the optimal solution, and confirmed our analysis by numerical results.

4.8 Space-Time Coded Asynchronous DS-CDMA with Decentralized MAI Suppression: Performance and Spectral Efficiency

In [60] multiple-input, multiple-output (MIMO) techniques were considered in an asynchronous code-division multiple-access system with a flat fading channel. A uni-

fied maximum-likelihood receiver, based on chip-level oversampling, was proposed to jointly suppress the multiple-access interference and perform the space-time decoding. Analysis showed that the system performance was determined by the product measure of the space- time code and the effective signal-to-interference-plus-noise-ratio (SINR). Three expurgated union bounds were proposed to approximate the bit error rate for different MIMO schemes and SNRs. Next, spectral efficiency was analyzed by applying a Gaussian approximation to the multiple-access interference. Numerical results showed that the chip-level oversampling, together with MIMO techniques, could effectively increase the spectral efficiency. The impact of channel estimation error on spectral efficiency was also investigated both analytically and numerically. Two tradeoffs were found in a lower bound of spectral efficiency. In the first tradeoff to optimize spectral efficiency, the increase of the number of users was shown to dominate the degradation of SINR. In the second tradeoff, increasing the number of training symbols in a fixed-length packet was shown to yield a higher SINR but a reduction in the amount of transmitted information. An optimal number of training symbols was found numerically as a function of the SNR and the packet length.

4.9 Parametric Density Estimation Using EM Algorithm for Collaborative Spectrum Sensing

In [65] it was shown that collaborative sensing of spectral occupancy could increase accuracy and relax the required sensitivity of individual sensing units. The collaborative sensing required knowledge about the densities of collected sensing statistics to form the correct decision statistics for the optimum likelihood ratio test. In this research, a parametric density estimation scheme using the expectation-maximization (EM) algorithm was proposed to estimate the parameters of densities that are drawn from a given family. When the log-likelihood function for the EM algorithm satisfied a certain condition, the maximization procedure was shown to require only a weighted sum of the collected sensing statistics. Numerical examples showed that in various scenarios the proposed EM algorithm produces more accurate estimates than the sample average does.

4.10 Throughput-Optimal Precoding and Rate Allocation for MISO Systems With Noisy Feedback Channels

In [62] a throughput metric was considered for a multiple-input single-output (MISO) system with noisy feedback of channel state information (CSI). The goal was to optimize a precoding matrix with a medium-access control layer metric. The problem was a nonlinear multidimensional optimization. Results showed that the optimal precoding turned into beamforming when the signal-to-noise ratio (SNR) of CSI feedback was sufficiently large. A necessary condition for the optimality of beamforming under the throughput metric was determined, and the necessary and sufficient condition was numerically found based on the Gauss-Chebyshev Quadrature method. Next, the rate allocation for beamforming and spatial diversity was analyzed. Then, a two-mode transmission scheme was proposed such that the transmitter was engaged in either the beamforming mode or the spatial diversity mode depending on the SNR of the CSI feedback. It was shown that at a fairly high SNR of CSI feedback, the rate allocation needs to be reduced, while at a low SNR of CSI feedback, the allocated rate should be increased. It was shown that when the SNR of CSI feedback is lower than a threshold, there always exists an SNR of the transmitted signal such that the CSI feedback can be viewed as the real CSI solely for the purpose of rate allocation. The result also showed that the throughput of two-mode transmission is almost the same as the throughput of the optimal precoding scheme, even with a low SNR and large feedback delay.

4.11 Increasing User Capacity by Interference Avoidance and Intentional Asynchrony in CDMA Systems

In [61] the number of users that can be supported at a given signal-to-interference ratio in asynchronous direct-sequence code-division multiple-access (DS-CDMA) systems was examined. It was shown that for many chip waveforms the user capacity for asynchronous systems is larger than for optimally designed synchronous systems. The degree to which the user capacity improves by exploiting asynchrony was characterized by defining the effective dimension of the chip waveform. Finally, simulation

results were shown to verify the analysis.

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